SOME PRINCIPLES

OF

SAFETY VALVE DESIGN

WITH SPECIAL CONSIDERATION OF VALVE SPRINGS
FOR LOCOMOTIVE POP SAFETY VALVES

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Safety Valve Springs*

THE spring is the heart of the modern pop safety valve; it is the essential element, to which all other details of design are subordinate. If the spring is not properly proportioned for its purpose, the satisfactory performance, discharge capacity and durability of the valve can not be secured. The operations of a poorly designed valve may be greatly assisted and improved by a suitable spring; and a valve with an excellent arrangement and relation of the other working parts and discharge passages may be seriously handicapped by an improperly designed spring or even transformed from a safety device to a source of danger.

The history of safety valve making indicates that the spring has been regarded as a relatively unimportant detail, made up without exact knowledge or study, following any general custom or usage that had seemed satisfactory in the past, and doing as well as might be within the dimensions conveniently available in valves designed primarily with regard to economy of material, pleasing proportions and uniform gradations of size, thus forcing all sizes of springs for wide ranges of pressure to go into the same body or casing.

A suitable and efficient spring must be the first consideration. A safety valve should be designed by calculating the total spring-load required to be exerted upon the disc when the valve is closed, then the amount of further compression needed for the pre-determined vertical lift of the disc when the valve opens, with a reasonable allowance for a reserve of further possible free movement of the spring in compression, and thereupon determining the dimensions of the spring that will carry this load at its point of greatest efficiency, with due regard for flexibility, sensitiveness with accurate adjustment, and durability in service.

There are several variable dimensions and factors that may be to some degree modified, in proper relation to each other, in designing springs to meet any given requirements, and several different springs may be laid out that will accomplish much the same results with but slight differences in allowance for the several factors that must be assumed; but there is a certain minimum limit beyond which it is impossible to go, and where the available space has been by custom or commercial considerations absolutely fixed, the obvious procedure is

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not to let it all go as a difficult problem having no rational solution, but to make the spring of a steel that permits greater fibre stress, to design an arrangement of valve parts which shall have the least throttling or retarding effect upon the steam which the spring does permit to escape, and to utilize all means to reduce the required total spring-load to the least amount without restricting the valve outlet diameter or area. Details of mechanical construction are thus important, but secondary, for the efficiency of the spring in its functions will after all determine the satisfactory performance of the valve. Modifications in valve design may help but can not cure a viciously ineffective spring. On the other hand, it is not always possible, within the limits imposed, to design a spring to overcome or counteract defects of valve design.

Some of the characteristics of helical springs are commonly known, but it may be well to review briefly the principles involved. The accepted foundation of the mathmetical theory of elastic solids is Hooke's Law, "Ut tensio sic vis," or, as the strain is so is the stress, and this is true of the spring, that within the limits of elasticity, the deformation or compression is proportional to the force or pressure which produces it; and in a spring of given dimensions, equal increments of force or pressure applied will produce equal amounts of compression. For example, if it requires a total load of 2000 pounds to compress a given spring having a total possible compression of one inch so that its coils are solid, with no further deflection possible, then a load of 1000 pounds would have caused this spring to shorten just one half of that amount or one-half inch, and each 100 pounds load more or less would cause a shortening or lengthening of 1-20 or .05 inch. The total amount of compression or shortening of a spring under load is divided equally among its free or effective coils, and as the amount of deflection under a given load is determinable by formula or by experiment for every combination of size of steel, mandrel diameter and pitch, the total compression of a spring is found by multiplying the deflection of each coil by the number of effective coils; and for any fixed proportions of diameter and pitch, the compression of a spring at any given load is proportional to the number of coils; therefore it is generally said that the long springs have greater compression than short springs and that the simplest way to increase the total compression or movement is to lengthen the spring. But of course an increased compression for a given load can be accomplished by changing other proportions without increasing the total free length.

This increase of compression of a spring in proportion to the

increasing number of its coils is independent of the total load which the spring will carry and does not affect that question. The strength of a spring, or the load which it will carry or sustain at any given proportionate amount of its total possible compression, is determined by the characteristics of the metal, the size or cross-section of the rod or wire and the diameter of mandrel on which it is wound; for example, if a load of 1000 pounds will compress a spring of certain diameter-dimensions one-half of its total possible compression or one-half inch then a spring of the same diameters but twice as long and having double the number of coils would be compressed by the same load one-half of its total movement or one inch; a load of 1500 pounds would compress either spring three-quarters of its total possible movement, and likewise either spring would be compressed solid under a load of 2000 pounds; the strength or carrying capacity of the two springs would be the same, although of different lengths, and the amount of deflection of each coil in either spring would be the same; although the total amount of movement would be different, a spring four inches long would be just as strong or would sustain the same load as a spring eight inches long; there would be no difference in their capacity or load strength. But the action of the two springs in safety valve service would be very different; for the longer spring would have its power exerted through a greater distance, with greater amplitude of movement or flexibility, and the oscillations set up by any sudden force would affect the behavior of the valve.

If all other dimensions remain unchanged, enlarging the cross sectional area of the rod or wire of which the spring is wound will make the spring stiffer or stronger or carry a heavier load for the same amount of compression; and of course square rod will make a spring slightly stiffer than round steel of the same diameter. There are some conditions which may be better met and special results that can be more readily obtained by using round section rather than square, and vice versa; and generally the controlling consideration is not merely the greater area or volume of the steel, but rather a slightly different characteristic reaction and activity, which can be considerably modified by slight alteration of other elements of the design. Reducing the mandrel diameter will also make the spring stiffer or stronger and thus admit less compression for the same load; while increasing the inside diameter or mandrel upon which the spring is wound will make the spring weaker or more flexible, and will decrease the amount of the load which it will sustain or carry for a given compression or will increase

the deflection of each coil and likewise the total compression which carries or balances a given pressure load.

Therefore the total amount of compression of a spring for a given load may be increased by increasing the number of coils of the same diameters and pitch and thus increasing the total free length; by reducing the cross-section area of the rod; by enlarging the mandrel and consequently also the over-all diameter; or by any or all of these modifications at the same time.

In making a safety valve spring, there are certain practical limitations which must be taken into account. Steel of very large diameter cannot be satisfactorily wound upon a small mandrel, and the flexural or bending strain becomes too great, so that a fracture or transverse set is developed. A spring excessively long in proportion to its diameter and pitch may bend or buckle instead of compressing in a straight thrust axially; and if the number of coils be too great, the reaction of the spring will set up an oscillation which not only permits but aggravates the undesirable and destructive chattering of the valve. The valve disc must not, in effect, be suspended at the end of a flexible spring, but must have behind it at all times a positive force capable of controlling its action when lifted by the escaping steam. If the spring be too short, not only will the reaction be too sudden, but the active free coils will form a smaller proportion of the total length; it is not then possible to distribute the pressure at the ends of the spring so evenly upon the coils, and the spring compression will be greater on one side than on the other, transmitting an undesirable side thrust to the disc guides. If the pitch is too steep or the coils wound too far apart, there will be room for considerable free movement and apparently a large possible deflection of each coil, so that it might seem as though only a few coils would give the total compression desired; but if this be attempted, the fibre stress upon the steel is enormously increased, the flexural strain becomes the larger factor, the rod is fractured or the elastic limit of the steel is soon passed and a permanent set takes place, destroying the essential properties of the spring before the required deflection of each coil can be attained. If too many coils are put into a given fixed length of spring the theoretical deflection required of each coil will be within safe limits, but there will not be sufficient free space between the coils to permit even the small necessary movement or compression, and when the pitch is thus too flat, the spring will have insufficient reactive power or force, because of the inadequate strain and fibre stress put upon the steel. The spring must thus have sufficient

force to make the valve open and close promptly and positively and keep the seat tight, not only to give prompt relief but to prevent the constant simmering and leaking which cuts and destroys the seats and permits the deposit of boiler-scale upon any exposed threads. The requirements of positive control and extreme lift are thus to a large degree contradictory.

The character in action and performance required of the spring in a pop safety valve is different from that expected of car springs or similar buffers. In carrying the load of a car or wagon, any unevenness of the road causes a jolting or bouncing, and the momentum of the moving car adds temporarily to the effect of its dead weight to increase the violent action of the spring. Under severe conditions such springs are often compressed to their limit, until the coils are in solid contact, and a severe bump or jar is felt in the car itself; but the reaction of the spring, when the unevenness is past, sets the car back to its proper position, and on the rebound it may be that the car has risen above its normal place so that the spring is drawn out in tension; after a while these waves of oscillation subside, and the car rides normally. For such service, car springs are generally designed so that when the car is loaded in ordinary manner the spring will be about one-half compressed, or one-half of its free movement will carry or balance the contemplated load. The reason is that this gives some leeway for additional load in the car without compressing the spring too much, and also permits the greatest movement above and below the normal medium position. It is believed that the conditions of longest life and least severe fracturing strain upon the car spring are met when the calculated ordinary load will thus compress the spring one-half of its total free movement.

For pop valve service, on the other hand, the conditions are different; the exact pressure load is determined from the exposed area of the disc and the steam pressure, and when the valve opens there is an added load governed by the additional area of the disc and the steam pressure, which rapidly decreases as the steam directly below the valve escapes and the boiler is relieved. Under no conceivable conditions of actual service can sufficient steam pressure be brought upon the valve disc to compress the spring so that the coils will be solid, metal to metal, if it has been reasonably designed for its original fixed load; and the additional spring compression to permit the valve opening in order to relieve the boiler is comparatively little, possibly 0.08 inch, more commonly and preferably less, and never under any conditions as much as 0.12 inch or say $\frac{1}{8}$ inch as an extreme amount. If after the

fixed load pressure is reached, the spring has still 15-32 inch of unused possible compression, of which less than 3-32 inch will be required to accommodate the desired lift of the valve, there will be still 3-8 inch more before the spring would go solid at which point all further compression would be impossible; therefore the valve spring can be properly designed to carry its set load at much more than half of its total free compression, and nearer to its solid condition than would be wise with a car spring where the amount of amplitude of total motion is not limited.

If springs are properly proportioned, the point of greatest resilience, elasticity and reaction, securing sharp action in the valve, and permitting the most sensitive and accurate adjustment of opening pressure, is in the last one-third of the total possible free compression, and this is the part of the spring action which should be utilized for safety valve service. I believe it proper to proportion the spring so that the set load is carried at about two-thirds or three-fourths of its total free compression, making the length and dimensions of the spring such that the remaining unused compression of the spring will be ample for the lift of the disc, and a safe margin beyond.

While it may be said that the springs will never be subjected to the extreme compression required to force them solid in service, yet the working compression is a large proportion of the total free movement and the spring might be dangerously near the point of setting or fracture unless properly proportioned and tempered to take the solid test. In making boiler tests the head bolt may be set down until the spring is solid, to close the valve; and if the valve is fitted with a lever, the spring may be at any time lifted or compressed an indefinite amount by that means, even to solid. I would not consider it proper to use in a pop safety valve any spring that would not safely take the solid test, capable of being compressed until the coils are metal to metal any number of times consecutively, without showing any permanent set or strain. Otherwise there will be nothing to prevent the spring from being screwed down, even through ignorance, until the danger point may be once passed, and the spring then takes a permanent set, after which it becomes entirely ineffective as a valve spring and a source of danger if its use is ignorantly continued.

One prominent manufacturer of safety valves requires all springs to be designed to take this solid test indefinitely. After the springs are made and tempered, they are closed solid in a press at least three times; and again before they are put into valves for service, at the time when

the ends are dressed and fitted, they are tested three times solid and the compression at the proper load for which they are designed is noted. If any spring shows a set or shortening, even temporarily, of as much as 1-16 inch in any of these tests, or if there is much variation in the compression at normal load, it is condemned and rejected. Out of the great number of valve springs made and tested every year under these conditions less than one-third of one per cent are rejected on this account, which shows that the requirements are commercially practicable and that the method of calculation and design is sound and conservative. Breakage of these springs in service is practically unknown. Such results demonstrate what modern methods with care and accuracy can accomplish, in producing uniformity of performance and reliability, and would be remarkable in any manufacturing operations where the number of pieces is so considerable, without taking into account the peculiarities of springs and steel.

If after the winding, tempering or testing, the finished spring is a little shorter than the standard length, there is a temptation to reheat it and pull it out a little to make it the full length, but such treatment is undesirable even if it be so skillfully done that the steel is not burned or overtempered. Not all springs so reheated would be inferior, but perfect security lies in accepting the small losses that may occur rather than assume any risk.

Springs of comparatively poor design, if well made of proper steel, heated uniformly to the temperature for working and tempered skillfully, are to be preferred to springs of better dimensions but improperly made. In most small shops where springs are wound by hand, the long bar of steel must be heated in comparatively short sections in a small furnace or forge fire, winding about a foot of the steel at each operation, drawing the bar by hand-tongs around a cold mandrel and then sticking the remainder of the straight bar again into the fire until it is soft enough to wind another coil or two. Each foot of the steel has been heated to a different temperature, and where the heated sections have overlapped, the steel is likely to be burned. The same difficulty arises in tempering, where it is necessary to move a large spring rapidly around in the fire to try to get all parts of it heated up at the same time; one end sticks out into the cold air while the other end is in the hottest part of the fire in the blast. No two springs made in this way can be alike, and different coils of the same spring will differ considerably in load-strength, temper, elasticity, resilience and breaking strain, for generally about one coil is all that can be wound at each

heating. The bars measure from five to twelve feet long for making springs for valves of the larger sizes, and for locomotive valves the lengths would be about four to six feet. The whole bar of steel should be evenly heated at one time, without being exposed to any direct de-carbonizing flame or forge blast, then wound accurately and quickly at one operation, and plunged in the tempering bath at exactly the proper moment.

These springs should be wound of a special grade of steel, kept up to standard specifications, in bars of the various sizes and shapes required for different loads and pressures; and although they are wound in the same general manner and have much the same outward appearance as ordinary coiled helical springs that are used for car springs and other commercial purposes, in reality they are very different in treatment and character, and proper results can never be obtained if springs of ordinary steel are substituted. No railroad should attempt to use car springs of similar shape that may be on hand, or to buy springs for safety valves by specifying simply the measured dimensions.

In measuring springs, it is the custom and better practice to state first the inside or mandrel diameter, then the free length of the finished spring and last the diameter and form of the steel rod used, the measurement of the cross-section being that of the straight bar before winding. For long springs it is sometimes necessary to use a taper mandrel to facilitate the drawing off of the spring, although generally the slight natural expansion of the spring after winding will sufficiently release it; where the mandrel is tapered, the mean diameter, approximately halfway between the two ends, is the dimension to be specified. The overall outside diameter will generally be slightly more, and the outer face of the coiled square steel will be less, than the commercial dimensions would indicate.

In any design and calculation of springs the factor of proper or permissible fibre stress must enter; and it is obvious that this amount of fibre stress can be stated or calculated to be any quantity which may be desired or may seem comfortable or convenient in the judgment of the engineer, by properly proportioning the various assumed factors and constants, which must be determined more or less arbitrarily in operating under any formula whatever. Whether we reason from Hooke's Law, or from the general statement that every action has an equal and opposite reaction, or appeal directly to the doctrine of the conservation of energy, it is plain that we can get no more work out of a spring in reaction than is put into it, and the more force or power in

compression that is put into a spring of given dimensions, the greater the amount of work which it will return and the sharper and more positive will be its action in controlling the valve. The way to get proper work out of a spring is to put force into it in effective stress.

In a paper by a member of the Society, Mr. H. V. Wille, of the Baldwin Locomotive Works, printed in the January number of the Journal of the American Society of Mechanical Engineers, he discusses difficulties that have been met with in designing stay bolts for locomotive fire boxes, where by reason of the expansion the bolts are stressed above the elastic limit, in flexure more than in tension. He argues that the obvious remedy does not lie in the use of a slow-breaking material but in the employment of steel of sufficiently high elastic limit to meet the conditions of service, and thus also to reduce the necessary diameter of the bolt and proportionately reduce the fibre stress in flexure. He states that stay bolts have recently been made of the same grade of steel as that used in the manufacture of springs, oil-tempered, to safely stand a fibre stress of 100,000 pounds per square inch, its high elastic limit making it possible to reduce the diameter so that the fibre stress in flexure is less than one-half that in the ordinary type of bolt and the material is capable of being thus stressed to a high degree. This same reasoning applies aptly to the problem of making suitable springs for safety valves, and practical experience has demonstrated that every argument and consideration is in favor of putting the steel under the highest practicable fibre stress. Safety here lies not in allowing a factor too large, but in using material of known and uniform quality and greater strength.

Low fibre stress is not a measure of safety but of ineffectiveness. To properly develop the resilience of the most trustworthy and suitable steel available today requires a stress that would be inadmissible with material of inferior temper or uncertain quality and subject to ordinary commercial defects. Experience shows that springs may best be stressed at from 60,000 to 75,000 pounds per square inch at the fixed load, which should compress the spring about 70 per cent of its total possible free movement, the remaining movement should be three or four times the further lift of the valve in opening. This is low enough for good steel and gives safe working limits and conditions, and under the same formula the stress when the spring is solid will not exceed 100,000 pounds per square inch.

The limit of elasticity, beyond which a permanent set occurs, is different for torsional strains than for elongation and is independent of

the tensile strength, and for steel of the proper characteristics for spring-making, this torsional elasticity is relatively high. Car-springs have sometimes been calculated upon a fibre stress as low as 30,000 pounds per square inch at normal load, and this may have seemed reasonable for common grades of steel under circumstances where the springs might be frequently subjected to the extreme compression or extension. But the material to be used today does not properly develop the power in reaction at any such small percentage of its total strength, and the fibre stress now recommended in the hand-books and in the modern text-books on applied mechanics is generally 80,000 pounds. This is not a question of keeping within limits of safety, but of stressing the steel to its point of proper efficiency. For example, it would be absurd to expect a spring suitable for use in a valve at 200 pounds pressure to show proper performance and lift or permit satisfactory opening and closing of the valve at only 50 pounds pressure; its reaction and resilience could not be at all reasonably developed.

If a spring is designed upon a formula which may indicate a fibre stress of 70,000 pounds per square inch at normal load, and as much as 100,000 pounds per square inch when compressed solid, yet is made of such steel that it can remain assembled in the valve indefinitely under pressure without perceptible set, and can be compressed solid an indefinite number of times without injury, it is evident that it is more properly proportioned and is used at a better and safer percentage of its elastic limit than springs made of less virile steel, that although calculated by some formula which indicates only 30,000 pounds per square inch fibre stress at normal load, will suffer a gradual set or deterioration in service or will become permanently set if tested solid. Of course it is obvious that certain grades of steel, whether on account of cheapness in methods of manufacture, lack of uniformity in character, or poor judgment in adaptation to the special purposes in hand, may show a set at a comparatively early point beyond the normal load, no matter at what figure it may be fixed; and therefore a fixed limit of fibre stress has no meaning unless the characteristics of the steel be also specified or known. Springs wound of bronze are notoriously inefficient and unenduring, and their depreciation and permanent set in service at comparatively low fibre stress will more than counterbalance any possible advantage of slow corrosion; and certain grades of steel may be as poorly adapted for the making of valve springs. The torsional elasticity and power depends not upon the tensile strength so much as upon the temper and resilience. Therefore some of the

new alloy steels have proved disappointing for this service and the name of any alloy can not as yet be used either as a fetich or a selling phrase.

Observation of many thousand springs in continuous daily service, under severest conditions of constant use, shows that springs calculated upon a very high fibre stress are entirely reliable for indefinite periods of service and do not develop any measurable percentage of faults or fractures; the failure of valves under operating conditions attributable to such springs is practically unknown and is less than the percentage due to the rare defects of the other structural parts.

The theory of the action of helical springs was developed between 1814 and 1848 by Binet and by Professor Thomson, who argued mathematically that the force opposing the elongation or contraction of the spring is the elasticity of torsion, which is independent of the elasticity of compression or extension in the rod; but all mathematical discussions of the nature of the action of helical springs have been simplified or made possible by eliminating or disregarding all consideration of certain practical conditions met with in practice. Green showed in 1830 that the general investigation of the relations between the stresses and deformations of any solid body depends in its simplest form upon the solution of a quadratic equation having six unknown quantities and twenty-one terms whose coefficients are essential, therefore we may pardon all the later investigators who have refused to include the further complications that consideration of the means of applying the pressure upon the ends of the spring and the flexural stresses would introduce, and have made a short cut by imagining the spring unwound and resolved back into the original straight bar of uniform section, in order to obtain any workable formula whatever; and we can understand why more do not rush in with easy experiments and confident amendments.

The very complete mathematical discussion of this whole subject by St. Venant, the French physicist, in 1855, with graphic illustrations of his conclusions, includes the consideration of round, square, triangular and many peculiar sections. He demonstrates what may seem at first rather startling, that the points of greatest distortion at the surface are nearest to the axis of the twisted section, that the least distortion occurs at the points farthest from the center, and that the stress and strain tend toward zero at projecting angles, either acute or obtuse. Thomson and Tait followed this with elaborate mathematical discussion and practical experiments. The more important flexural distortions,

in bending the steel and winding the spring, as well as the torsional strains, are along the outer and inner faces of the square section in each coil and to a less degree along the lateral faces, at both the short diameters of the section and not through the corners; as may be very roughly illustrated by winding a square rod of soft rubber into helical form.

But the actual spring is not even approximately a straight bar held firmly at one end and twisted uniformly; and the pressure is not applied at the extreme end of the bar but upon a flat plate or thimble at either end, fitted when the spring is free and not when more or less distorted under load, but intended to transmit the pressure as nearly in a straight line along the axis of the mandrel as conditions will permit. The violent distortion of the cross-section of the square steel rod, which by no stretch of imagination can be considered as still rectangular, sets up internal stresses in the tempered steel, which must be recognized even if they cannot be conveniently measured. The strain of deflection of each coil, of even moderate pitch, amounts to a serious item, but is expressly brushed aside and ignored in deriving the ordinary working formulæ.

Springs should be very gradually and uniformly heated without decarbonizing the surface skin by exposure to any flame, and the excessive hardness or temper of the surface afterward drawn by reheating to a relatively low temperature. This reheating seems to give a toughness to withstand greater tensile strain and is especially important in proper consideration of the generally neglected factor of lateral or flexural strain which becomes so large when any set or fracture of the spring occurs. I am persuaded that much of the virtue and special character of the spring lies in the molecular tension and condition of the surface skin after tempering.

Although the chief element in the power of a spring is its torsional strain developed in the compression, and the flexural stress may be comparatively a small part of the useful power or resilience, yet the destructive set experienced from over-compression in springs of few coils with steep pitch, can be shown, I believe, to be more commonly due to exceeding the elastic limit in the bending strains than to any severe strain in torsion; and this flexural stress increases as steel of larger cross-section is employed; but no one has yet been willing to risk a statement of the influence or effect of variation of pitch, as a definite factor in any generally accepted formula.

In springs made of square steel it may very well be that the re-

heating to draw the surface temper affects the corners most and the lateral faces only slightly less, and that the toughened metal in the corners backs up or strengthens the harder interior portions; the internal strains would be relieved, while an approximately cylindrical interior would retain a high temper to resist the truly torsional stress of compression. The slightly variable temper in the corners and lateral faces of the square steel may be the better disposed and adapted to accommodate the several varying strains in a helical spring; for the symmetrical form of the round steel, even when the temper is slightly drawn after hardening, permits little relative adjustment of the several lateral and torsional strains, and the round section can be considered as subject to considerable unrelieved internal strain in flexure.

The spring must have sufficient compression to afford the amount of valve-opening fixed upon as reasonable and practicable, yet be kept within the least amount of movement that will satisfy these demands, for every spring has considerable eccentricity, depending upon the pitch and proportions of the coils, and under the increasing compression or extension as the valve opens or closes, the ends have a movement which may be likened in some degree to the actions of the free end of a fire-hose under pressure. The side-thrust due to this twisting and untwisting eccentricity is transmitted to the valve disc and guide wings, and increases rapidly with each fraction of increased lift or opening of the valve.

Large movement of the spring in compression is undesirable; it is but a necessary means to an end, an evil to be kept within minimum limits. The chief object of a safety valve is not to lift the disc but to release steam; not to perform internal work in the valve but to relieve the boiler. It would be an advantage if satisfactory discharge through the valve could be attained with even less spring compression than at present. Large lift of the disc is not merely a measure of capacity but of inefficiency; for the valve which releases the steam with the least proportional lift or spring compression is to that degree the more efficient for its purpose and at the same time more safe and reliable.

The specifications which require valve seats to be made of non-corrosive metal and the rules which compel every valve to be tried and lifted by the lever every day, aim to overcome the ever-present danger that the valve may stick upon its seat and fail to open at the critical moment; but the greatest cause of the sticking of the valve, when it does occur, is not corrosion of the seat face but the binding

friction of the disc-guides against the side of the well or throat of the valve. This cocking or binding effect can be decreased by any modification of design which will reduce the diameter of the cylindrical guide, or which will eliminate the friction of the lower ends of the guides and bring the guiding surface close to the plane of the seat; both of these modifications reduce the moment of the friction or cocking stress. Any device which reduces the lift of the disc and the spring movement to the least possible amount will also reduce the eccentric spring action and its effect, and of course any valve design which requires or contemplates an unnecessarily large lift or compression disadvantageously magnifies this effect. It is perhaps important to point out that as the primitive and still common form of safety valve has a seat opening beveled at an angle of 45 degrees with the vertical spindle, the effective passage through the seat is measured by the sine of 45 degrees and is approximately only 0.7 of the actual vertical lift or compression of the spring when the valve opens, so that the spring must necessarily compress about one and one-half times the effective lift, and even this does not always afford a free passage for the steam to the air where there is vertical overlap of the regulating ring against the lip of the disc in order to increase the lift against the greater pressure of the shortening spring.

In the well-known annular type of valve, the area of the disc between the seats open to the constant pressure of the steam is approximately only four-fifths of the total initial area of the disc under load in the bevel-seated form of valve having the same diameter and seat circumference; therefore the use of the familiar annular, flat-seated valve is the logical way to reduce to a minimum all the difficulties of spring making, especially where the space available for the spring is absolutely limited by the over-all dimensions permitted by locomotive builders and boiler makers; for the spring need thus be of dimensions and strength to carry only four-fifths of the load necessary in the lip-type of valve; the vertical lift and spring compression require to be only 0.7 as much, or for the same lift will give one and one-half times as much discharge area; and no preliminary lift is required to relieve the overlap of an adjusting ring, for the work of giving to the disc its sudden pop lift is performed by an auxiliary steam discharge by-passed through the central passages. This by-passed or auxiliary discharge adds its volume to the main discharge capacity and leaves an absolutely unrestricted and unthrottled free escape for the main flow of the released steam directly to the open air, without any tortuous expansion chamber

or deflecting ring; the outlet is across a flat seat which not only utilizes the full vertical lift but gives a discharge opening of cylindrical form with efficient rounded edges. This form of disc has the further advantage that it is impossible for it to jam or stick and it is easily refaced by rubbing on a face-plate instead of grinding to a bevel; and as the disc can be made entirely without the ever-cocking and sticking guides, the efficiency of the spring can be thus aided and utilized to the greatest possible degree. My emphasis upon this point of spring limitation and the helpful effect of suitable valve-seat design is because attention has not been generally called to its importance and experience has shown the serious difficulties which may be thus minimized if not entirely avoided.

It is not within my purpose to recommend any definite formula for the calculation of helical springs. My investigations have led me to believe that there are not in this country today many men who have experienced the fortuitous concurrence of time, inclination, business necessity and proper manufacturing and testing facilities to lead them to develop a practical working formula very far beyond the very unsatisfactory rules laid down in the hand-books. Experiments have been carried out upon springs wound of comparatively small wire, but every one who has had occasion to use the conventional formulæ must have realized that no matter how well they cover a few types of car-springs within a limited range, they lead us far astray in this special branch of the problem; especially in cases where the limitations upon the free length of the spring will not permit the use of either round or square bars and some special flat or rectangular section must be used to secure the required area of steel and still leave room for movement between the coils.

One engineer to whom I wrote replied: "I would say in reference to the questions raised by you, that I do not consider it good practice to use a stress of over 95,000 or 100,000 pounds for valve springs, although we have in our various experiences stressed springs as high as 145,000 and 150,000 pounds, but we do not under any circumstances recommend this or any approximate stresses for the extreme service to which valves are subjected. Regarding this question of stress, I would further say that a long time ago we demonstrated that while various published formulæ are correct within certain limits for springs made of round steel, they were far from being correct for springs made of squares and special sections. We devoted a great deal of time to both theory and experiment to demonstrate the formula which we now use, and

which we have proved by exhaustive experiments to be correct. We know that by using numerous published formulæ that some springs will show very excessive stress; however, these excessive stresses are not actual, but apparent, due to errors in the formula. The formula which we use being the result of years of experience, experiment and calculation, you can readily understand is not published, and furthermore, would be useless without the accumulation of data and special information which we have."

My aim has been rather to state conclusions derived from experience and observation and from the counsel and advice of those oldest and wisest in this work as well as from an inheritance of the results of thirty years of special study and experiment in this limited field. I have reviewed the several practical considerations that must be taken into account, so that in the discussion of the general subject this important element of the spring may have its due attention.

Nearly every engineer of education and experience would be qualified and perhaps ready to suggest at least one apparently simple and more or less obvious improvement in the design of safety valves or springs, but nearly every such possible detail will be found to be already old. Almost every conceivable device and modification has been the subject of a patent, and most of these have been thoroughly tried, with much expense and enthusiasm, before being condemned and discarded. The various subterfuges of double or concentric springs, one more flexible than the other, of spiral springs with coils of increasing diameter, whose first movement in compression is rapid until the smaller and stiffer coils are brought into action, springs suspended in all sorts of universal bearings, and every method of end bearing and fitting, have all been tried and abandoned by almost every maker and user of safety valves, but are periodically revived or rediscovered by some new designer or foreman and brought forward for consideration again and again. Before any such expedients are advocated, a study of the old file of long-expired patents would be enlightening and interesting. Attempts at using extension springs, in place of springs to be compressed as the valve opens, can be seen in patents and experimental valves of twenty-five years ago; but the idea has been generally abandoned, for not only is it difficult to devise any satisfactory end-fastening which will take firm hold of the steel without inducing a fracture there, but such a spring could be easily and ignorantly overstrained and set, while a safely proportioned compression spring can not take a set within its possible limit of movement, even to solid; and the side-thrust due to

unevenly disposed coils is found in extension springs also, wherever the springs have not the suitable length to permit proper proportioning and balance.

It would serve no useful purpose were each engineer to attempt to specify the exact dimensions of the springs to be used in safety valves for each pressure and service, for the limitations of special cases and the several conditions to be taken into account, with their relative importance and weight in the problem, would require the exercise of judgment to be derived only from personal experience, and any general rule would be burdened with a long catalogue of exceptions more troublesome than helpful. But the general principles rest upon a solid foundation, and any one may judge whether the springs in his safety valves satisfy certain rational requirements; but we must not expect to reconcile mechanical contradictions nor ask for valves that would demand miracles in springs.